SPATIAL DATA MODELLING, DUAL PARTITIONS AND THE SPECIFICATION OF SEMANTICS

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ABSTRACT:
The main objective of GSDI is data sharing and integration. This requires the formulation of standards for data exchange. Most standards developed to date take mainly care of issues like the technical specification of spatial data structures, spatial operators and meta data. Even with these standards the user community will face significant problems in data sharing because hardly any standards are provided yet with respect to the semantic aspects of geo-information. Semantics is generally embedded in specific application contexts so that knowledge of such a context is a prerequisite for understanding the semantics of data. Yet some of the formal and theoretical aspects of spatial data modelling will be guiding the specification of data semantics, so that a proper understanding of these aspects will be essential in this respect. These issues will be discussed in this presentation. A mathematical formalization allows the formulation of rules for specifying spatial data models relating thematic and geometric data, based on the combination of spatial and thematic partitions. This *dual partition structure* can be seen as a constraint for unambiguous semantic specifications; this constraint implies the direct relationship between thematic and spatial object descriptions. Furthermore if we require that semantic specification of spatial data should always comply with this constraint then it should be maintained under the process of object aggregation or data generalization. This implies that semantic specifications of spatial objects can (or should) generally be understood in a multi aggregation (or multiscale) context.

1. INTRODUCTION

Data sharing and integration in a GSDI context requires the formulation of standards for data exchange. Presently organizations like OGC, ISO and other national and international working groups are working hard to develop such standards for data formats, data structures, data type definitions, operators and for the specifications of meta data. Systems developers and data providers make sure their products comply with these standards. These standards take mainly care of the technical aspects of data exchange and are of great importance for the development of geo-informatics. But even with these standards the user community will face significant problems in data sharing because no standards are provided yet with respect to the semantic aspects of geo-information. Question is whether this is possible or even desirable. The semantics of spatial representations is generally embedded in specific application contexts so that knowledge of such a context is a prerequisite for understanding the semantics of data. Yet some of the formal and theoretical aspects of spatial data modelling will be guiding the specification of data semantics, so that a proper understanding of these aspects will be essential in this respect. These issues will be discussed in this paper.
Starting from some fundamental aspects of the spatial representation of geo-objects we can formulate a mathematical model for the interrelationships of thematic and geometric descriptions, see (Molenaar 1998). This model is fundamental for the specifications of unambiguous terrain descriptions, based on the combination of thematic and geometric partitions which we will call the *dual partition structure*.
This dual partition structure can be seen as a constraint for unambiguous semantic specifications; this constraint implies the direct relationship between thematic and spatial object descriptions. Furthermore if we require that semantic specification of spatial data should always comply with this constraint then it should be maintained under the process of object aggregation or data generalization. This implies that semantic specifications of spatial objects can (or should) generally be understood in a multi aggregation (or multiscale) context.
We will discuss several aspects of this model emphasising the relationship between the thematic specification and spatial resolution. Two approaches will be discussed:

1. The first approach is based on the relationship between the generalization levels of thematic class hierarchies and the related aggregation levels of spatial objects, the so called class driven object aggregation.
2. The second approach is based on functional aggregation hierarchies for spatial objects. Spatial objects are aggregated to form new functional units at a higher level. Each level will have its own thematic classification system.

From both approaches we will discuss how the semantics of objects is embedded in a multi scale or multi resolution setting. For both approaches we will give two examples:

a We will see how each approach supports data generalization processes through aggregation procedures.

b We will see how each approach can be used to develop methods for information extraction from remote sensing data.

2. THE SPATIAL EXTENT AND BOUNDARY OF OBJECTS

We will follow the line of thought developed in (Molenaar 1998). Let M be a spatial database containing a terrain description and let U_M be the collection of all terrain objects represented in this

database, i.e. U_M is the universe of M. We will assume that the geometry of the objects is represented in a vector format with a full topological structure, i.e. the geometry is described in nodes, edges and faces defining a geometric partition of the mapped area (or 0-, 1- and 2-cells). Let *Geom(M)* be the geometric component of M, i.e. it is the collection of all geometric elements describing the geometry of all objects of the universe. Let *Face(M)* be the collection of all faces in *Geom(M)*; similarly *Edge(M)* is the collection of all edges and *Node(M)* is the collection of all nodes.
The function $Part_{22}[\ f,\ O]$ will be introduced to express the relation between a face $f \in Face(M)$ and an object $O \in U_M$. If this function has the value = *1* then the face belongs to the spatial extent of the object, if the value = *0* then that is not the case. We can now define the set:

$Face(O) = \{\, f \mid Part_{22}[\, f, O] = 1\}$

Face (O) is the spatial extent of *O*. In this notation the geometric description of the objects is organised per object. For each edge *e* we can express its relationship to a face *f* by the functions:

$Le[\ e, f\ ] = 1$ if *e* has *f* at its left-hand side and
$Le[\ e, f\ ] = 0$ otherwise,

and similarly

$Ri[\ e, f\ ] = 1$ if it has *f* at its right hand side and
$Ri[\ e, f\ ] = 0$ otherwise.

With these functions the relationship between an edge *e* and an object *O* can be established:

$Le[\ e, O \mid f\ ] = MIN(\ Le[\ e, f],\ Part_{22}[\ f, O])$ and
$Ri[\ e, O \mid f\ ] = MIN(\ Ri[\ e, f],\ Part_{22}[\ f, O])$

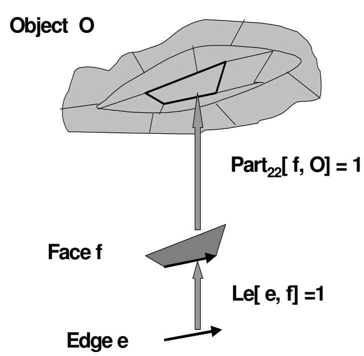

Figure 1: Relationship between edge, face and Object

If the edge has the face at its left hand side and the face is part of the spatial extent of the object then both functions on the right hand side of the first expression have the value = *1* and therefore the first expression gets the value = *1*. This means that the edge has the object at its left-hand side and thus we get $Le[\ e, O \mid f\ ] = 1$, otherwise it will be = *0*. Similarly if the edge has the object at its right hand side then $Ri[\ e, O \mid f\ ] = 1$ otherwise = *0*. If there is a face for which $Le[\ e, O \mid f\ ] = 1$ then that implies that the edge *e* has object *O* at its left-hand side, so that $Le[\ e, O\ ] = 1$. Otherwise $Le[\ e, O] = 0$. and similarly for $Ri[\ e, O\ ]$. With these two functions we define:

$B[\ e, O] = Le[\ e, O\ ] + Ri[\ e, O\ ]$

If the edge has the object at its left and right-hand side this function has the value 2. If the object is only at one side, so that the edge belongs to the boundary of the object, the value will be 1. If the edge is not related to the object then the value will be 0. The boundary of the object is therefore the set of edges for which this function has the value 1:

$\partial O = \{\ e \,/\, B[\ e, O\ ] = 1\}$

3. SPATIAL AND THEMATIC PARTITIONS

The universe U_M is a *complete coverage* if for every member f of *Face(M)* there is at least one object O so that $Part_{22}[\ f,\ O] = 1$. That means that objects cover the whole area covered by the geometry of M.
The universe is a *spatial partition* if it is a complete coverage and if the objects do not overlap, i.e. for each face f of *Face(M)* there is exactly one object O so that $Part_{22}[\, f, O] = 1$.

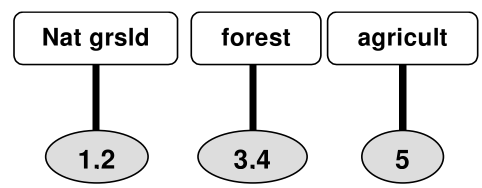

Figure 2: A collection of classes forming a thematic partition

Now let $P = \{\ C1,\ C2,\ \dots\ ,Cn\}$ be a collection of classes so that for each i we have $Ci \subset U_M$. P is a *thematic partition* of U_M if each object is a member of exactly one class. This means that the classes are properly specified so that the thematic description of the objects is unambiguous, see Figure 2 and 3.
If P is a thematic partition of U_M and U_M is a spatial partition of M then P *generates a spatial partition* of M. That means that the classes cover the whole mapped area and they are spatially distinct; see (Molenaar 1998).

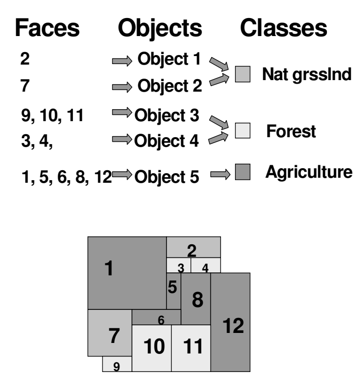

Figure 3: Objects and classes form a dual partition structure, i.e. the combination of a spatial and a thematic partition

This has been illustrated by Figure 3 where:

The set of faces is
$F_M = \{f1, f2, f3, f4, f5, f6, f7, f8, f9, f10, f11, f12\}$
The universe of the map is
$U_M = \{O1, O2, O3, O4, O5\}$
The collection of classes is
P = {Natural Grassland, Forest, Agriculture}

We see in Figure 2 that P is a thematic partition because each object belongs to exactly one class. U_M forms a spatial partition because each face of F_M belongs to exactly one object from U_M. We can see that this implies indeed that P generates a spatial partition, i.e. the classes cover the whole mapped space and there are no spatially overlapping classes. This data set has a dual partition structure.

Hierarchical partitions
If several thematic partitions $\{P_1, P_2, ..., P_\pi\}$ have been specified for U_M so that for any combination P_k and P_{k+1} the relation between the classes of P_k and the classes of P_{k+1} is n:1 (many to one), then these thematic partitions form a hierarchy. This can be expressed as follows:

let $\Pi = \{P_1, P_2, ..., P_\pi\}$ *be a collection of partitions*
then Π *is a hierarchy of classes if*
$(\forall C_i \in P_k | k < \pi)(\exists C_j \in P_{k+1}) \Rightarrow (C_i \subseteq C_j)$
and Π *is a strict hierarchy if*
$(\forall C_i \in P_k | k < \pi)(\exists C_j \in P_{k+1}) \Rightarrow (C_i \subset C_j)$.

These definitions imply that the partitions of the collection Π are ordered, so that each partition contains the classes of a particular level of this class hierarchy, P_π represents the highest level of the hierarchy and P_1 the lowest level. Because every P_k is a partition each object of U_M is always a member of exactly one class of each level of the hierarchy, see Figure 4.

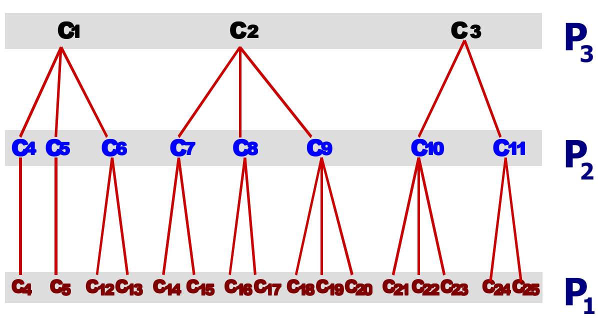

Figure 4: Classification hierarchies (Molenaar, 1998)

The definition states that in a hierarchy every class of each level (with exception of the highest level) is always a subset of some class at the next higher level, in a strict hierarchy it is always a *proper* subset of some class at the next higher level. Consequently every class of a level (with exception of the lowest level) in a strict hierarchy contains always two or more subclasses at the next lower level. If the hierarchy is not strict then there may be classes that contain exactly one class at the next lower level.

4. THEMATIC OBJECT AGGREGATION

4.1 Class driven aggregation

Suppose that a database contains the situation of Figure 5.a; this is a detailed description of a terrain situation with different types of land use (Liu, 2002). A less detailed spatial description can then be obtained, if the original objects area aggregated to form larger spatial regions per major land use class. This less detailed description can be obtained in two steps:
1. First the objects are assigned to more general classes representing the major land use types.
2. Then mutually adjacent objects are combined per class to form aggregated objects..

A consequence of this procedure is that there can be no two adjacent aggregated objects that are of the same type, i.e. that belong to the same land use class. This has been illustrated in the aggregation step from Figure 5.a to 5.b.
The original objects form a geometric partition of the mapped area and the classes form a thematic partition of the universe of the map. The relationships between the classes at different levels of class generalization form a hierarchy, so that the classes at each level of this hierarchy form a thematic partition according to Section 3. We saw in the previous section that when a collection of objects forms a geometric partition before aggregation, then the new collection after aggregation will also form a geometric partition. The combination of these two observations implies that when the aggregation procedures of this section are applied then the dual partition structure will be maintained. In the terms of (Molenaar, 1989) we can say tat this procedure transfers a single valued vector map into a new single valued vector map (Molenaar 1989, 1998).

4.2 Similarity driven aggregation

Generalization
This aggregation procedure is quite different from map generalization processes because it does not necessarily eliminate all small objects. This class driven aggregation process generates objects at a higher (more general) thematic class level; so the thematic content of the data set is driving the process not the resolution or scale of the (graphical) representation.
If small objects should be removed then a special step is required to identify these objects. A size criterion has been applied to the objects of Figure 5.b, the results are shown in Figure 5.c. These selected objects have no neighbours with a common super class, therefore a criterion can be formulated to measure the thematic similarity of these objects and their neighbours (Yoalin, 2002), (Bregt and Bulens, 1996). In the step from Figure 5.c to 5.d these objects have been merged with the neighbours that were most similar according to such a criterion. This similarity driven procedure is in fact a modification of the class driven approach; the strict requirement for the aggregation of objects with a common super class has been relaxed by the use of a similarity measure thus allowing a wider range of applications. But in both approaches it is the thematic similarity (or thematic generalization) that drives the process so that spatial resolution depends on thematic specification.

Image analysis
The similarity driven approach has also been applied to the data set of Figure 6.a. (Gorte, 1998) This figure gives an example how

this method can be used for RS image interpretation. Figure 6.a Gives a part of a SPOT XSS image of Ameland, one the islands in the North of the Netherlands. Figure 6.b. shows a first image classification result with segments that have been identified under different spectral classes which could be related to land cover classes. The variety of spectral classes in this area is often due to local variations which were not relevant for land cover classification, this resulted in the identification of too many and too small area land cover segments (objects). Therefore similarity measures have been formulated between these spectral classes; adjacent segments could now be aggregated into larger units by a stepwise relaxation procedure based on these similarity measures. The results are shown in Figure 6.c and d, the last result proved to give a relevant output for land use mapping in this area.

5. FUNCTIONAL OBJECT AGGREGATION

5.1 Object aggregation and generalization

It is certainly not always so that object aggregation can be achieved within the framework of one class hierarchy. In many cases objects will be aggregated to form new functional units. This is illustrated in Figure 7 where houses and factories are assigned to a more general class of buildings, but then these buildings and the lots they are on form real estate units and a contiguous set of these units forms a street block. Similarly sidewalks and roadways form streets.

These aggregation steps follow a bottom-up procedure in the sense that starting from the elementary objects composite objects of increasing complexity are constructed in an upward direction, in Figure 7 from left to right (Smaalen, 2003). These rules for the construction of aggregates are based on topological (adjacency) relations between objects, as in the previous section; in Figure 7 the elementary objects that form an aggregated object are linked by a connected adjacency graph. But the semantic rules are no longer specified within the context of a class generalization hierarchy or based on thematic similarity rules.

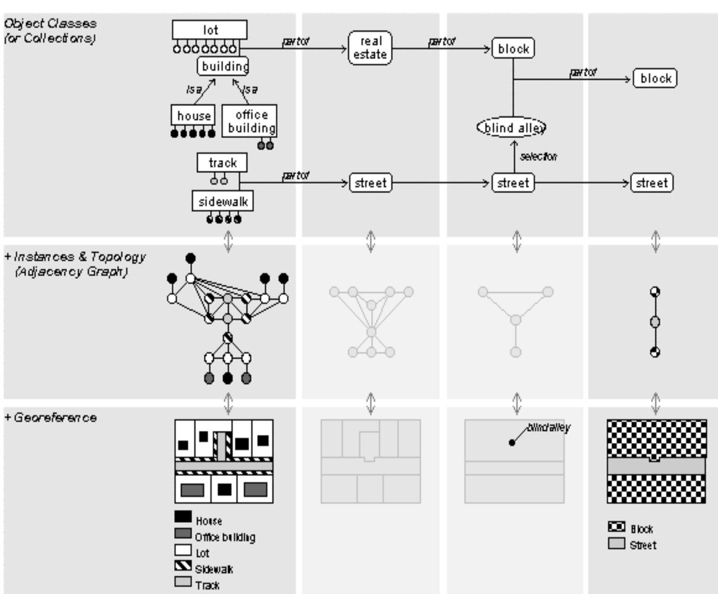

Figure 7: Functional object aggregations in an urban land use context (Smaalen, 2003)

This method has been applied to the topographic data of Figure 8. This figure shows how houses gardens and streets are aggregated in two steps to urban land use units. Similarly farm plots are aggregated to from generalised units under the class of agricultural land use. The source data for these figures have been taken from TOP10 Vector Dataset from (1:10 000 topographic map) the Netherlands Topographic Service.

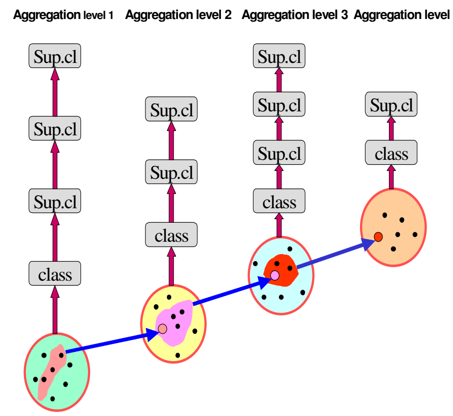

Figure 9: Classification hierarchies related to aggregation levels (Molenaar, 1998).

5.2 Aggregation levels and classification systems

Each aggregation level within such a hierarchy will have its own (sub) context within a thematic field, expressed through a classification system with related attribute structures. This means that each aggregation level requires its own thematic definitions implying that each aggregation level will have its own classification hierarchy.

This should be structured so that the generated attribute structures provide the information which is relevant for the objects at each aggregation level, see Figure 9. In the example of Figure 7. the levels refer to urban land use. The different (sub)contexts are related by the fact that sets of objects at one level can be aggregated to form the objects at the next higher level. There are often also relationships between various classes of the different class hierarchies related to the aggregation levels.

There are bottom-up relationships between the objects at different levels in the sense that the state information of the lowest level objects, as contained in the attribute data, can be transferred upwards to give state information about the objects at higher levels. There are also top-down relationships in the sense that the behaviour of lower level objects will be constrained by the information contained in the higher level objects. Such vertical relationships have also been defined in the context of general systems theory (Bertalanfy, 1968). In (Klijn,1995) they have been observed in the context of landscape ecology.

5.3 Image analysis

Functional object aggregation hierarchies can also be used for remote sensing data (image) analysis. We will follow the example of (Zhan, 2003). Zhan used the combination of IKONOS Multi-Spectral data and laser altimetry data obtained with the TopoSys I laser scanner. The example refers to an area of 3 x 3 km^2 in the south eastern part of Amsterdam. The TopoSys data have been processed to generate height data with an accuracy of about 15 cm in grid with 4 m spacing. The IKONOS data were interpreted into cover classes per pixel, these were: built-up area, vegetation and water. By combining these results with the height data they could be interpreted in second step into the classes: building, road, open paved area, grasslands, trees and water surface. These were class labels assigned per pixel. From these labelled pixels image segments could be formed presenting spatial objects. The identified buildings could be further classified based on their size and the height data. These classification results were the input of figure 10.a. Through a triangulation based technique spatial clusters of similar objects were formed as in Figure 10.b. These clustered objects were then aggregated into the urban land use units of Figure 10.c. When the results of Figure 10.b are combined with road data then the classified street blocks of figure 10.d are obtained. We see that this method for image analysis has been based on a semantic approach based on the functional object aggregations, i.e. each aggregation step specifies functional units at a higher level in the context of urban land use. In this example we go from the level of classified pixels, to elementary objects and then on to land use units or street blocks.

6. DISCUSSION AND CONCLUSIONS

The discussions in the previous sections of this paper illustrate several issues with respect to the specification of the semantics of spatial data. When discussing these issues we should keep in mind that the focus of this paper was on object structured approaches. The representation of spatial objects has two aspects:

1. The structure of such representations specifies which data types play a role in these representations and what relationships may occur between data of these different types.
2. The semantics of such representations specifies how database representations refer to "real world features". Semantics is understood here in the sense of (Winteraecken, 1987)

The previous sections dealt mainly with issues related to the first aspect. The semantic issues were dealt with only implicitly in the examples. From these examples we can learn that the semantics of objects should always be understood in an application context. Such a context generally refers to some spatial process be it natural, man-induced, social or economic. Objects play then the role of process response units so that their semantics can not be specified without reference to such a process. Therefore the semantics of object definitions will generally be hard to understand outside the context given by such a process. This implies that it will hardly be possible to standardise semantic object definitions.

The structural aspects of spatial object representations have been formulated with in the context of formalized data models. These models have a mathematical structure which helps us to understand some fundamental constraints that should be fulfilled to avoid ambiguity in spatial object representations. The relation found in Section 3 between spatial and thematic partitions appeared give an essential constraint for the specification of objects and object classes.

CONCLUSION 1
The dual partition structure, i.e. the combination of thematic and spatial partitions, is fundamental for the specification of semantically unambiguous and complete spatial representations.

This conclusion implies that spatial objects can not be considered in isolation because changing the geometry of one object, removing an object or entering a new object has an effect on the structure of spatial partitions. Similarly removing or entering object classes has an effect on thematic partitions and possibly also on geometric partitions.

CONCLUSION 2
The dual partition structure mentioned in Conclusion 1, implies that spatial objects should not be seen in isolation. Spatial objects should generally be understood as components of a spatial complex.

Due to the dual partition structure temporal changes rarely affect individual objects but affect complexes of objects, therefore:

CONCLUSION 3
Spatial objects should generally be understood as components of dynamic spatial complexes.

We saw that due to the dual partition structure thematic class generalization should be followed by a class (or similarity) driven object aggregation. Functional object aggregation requires a newly defined classification system for the aggregated objects. These combined operations are required to maintain the dual partition structure which is important to maintain the consistency of the semantic specifications of spatial data sets.

CONCLUSION 4
The dual partition structure should be maintained when object aggregation (generalization) procedures are applied to spatial object data. This is important for maintaining the consistency of the semantic specifications of spatial data sets at each aggregation (generalization) level and for maintaining the consistency between levels.

Earlier in this section we stated that the semantics of spatial object representation should be understood in the context of spatial processes (specified in an application context). The situation is generally more complicated when object behaviour is seen as the resultant of the interaction of processes at different aggregation levels. For instance the land use development within an urban district will be affected the socio-economic developments of the urban area which it is part of. But the development of the street block will also be constrained by its inner structure, i.e. the characteristics of its constituent components. This means that the behaviour of objects is constrained by processes at a lower and at a higher aggregation level.

CONCLUSION 5
Object semantics should be understood and specified in multi aggregation level (multi scale) context.

The examples of this paper referred to 2-dimensional situations. The conclusions are, however, equally valid for 3-dimensional approaches.

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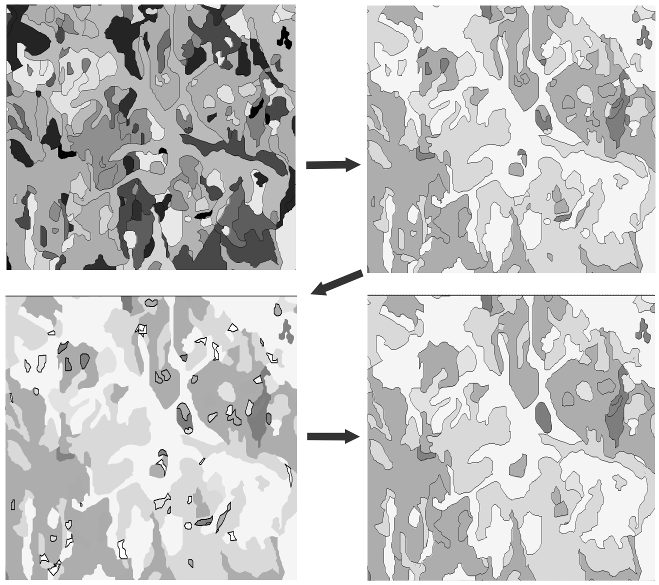

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Figure 5: Class driven aggregation of land use units (Liu, 2002).

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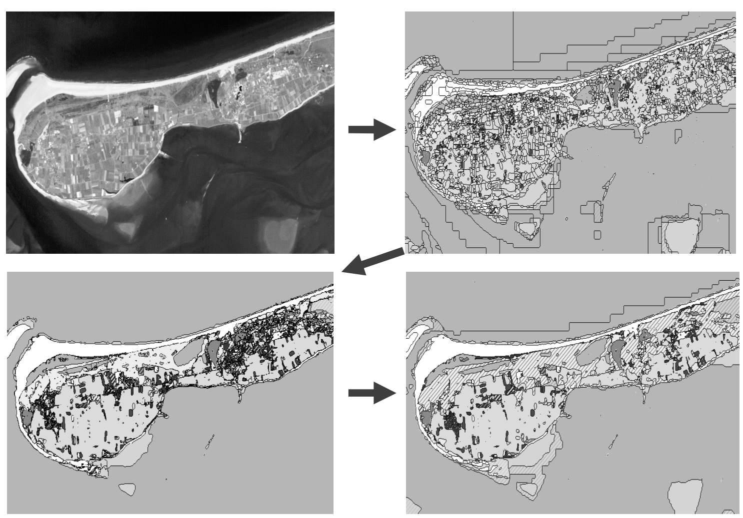

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Figure 6: Thematic similarity driven object aggregation hierarchies as a tool for rs-image interpretation (Gorte, 1998)

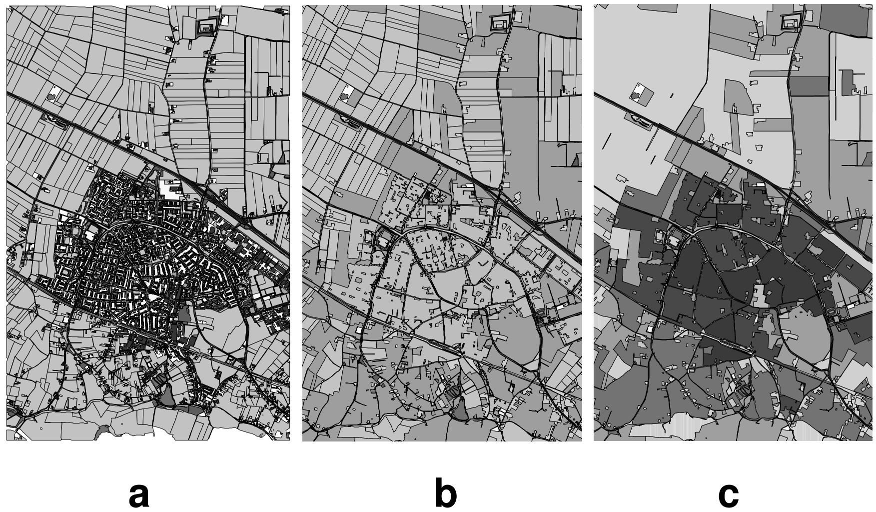

Figure 8: The generalization of topographic data based on a functional object aggregation approach (Smaalen, 2003)

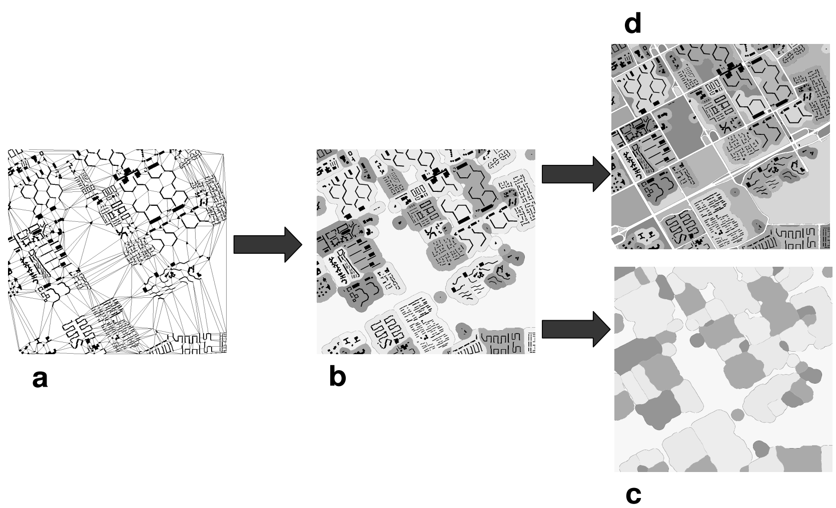

Figure 10: The identification of urban land use units through rs-image analysis based on a functional object aggregation approach (Zhan, 2003).